Non-Rare Earth Electric Motors

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Oak Ridge National Laboratory
National Transportation Research Center

2017 U.S. DOE Vehicle Technologies Office
Annual Merit Review

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Overview

Timeline

- **Start – FY17**
- **End – FY20**
- **17% complete**

Budget

- **Total project funding**
  - **DOE share – 100%**
- **Funding for FY17: $ 1,478K**

Any proposed future work is subject to change based on funding levels

Barriers

- Even without using rare earth PM material, DOE EDT 2020 cost targets are challenging.
- PD and SP targets will be difficult to meet with alternative technologies
  - Field excitation
  - Synchronous reluctance
  - Switched reluctance
  - Non-RE PM
  - Induction

Partners

- BorgWarner
- NREL
- AMES/DREaM
- University of Wisconsin, Madison
- ORNL Team members
  - Jason Pries
  - Lixin Tang
  - Randy Wiles
  - Radhakrishnan Balasubramaniam
  - Tolga Aytug
  - Andy Wereszczak
  - Amit Shyam
  - G. Muralidharan

Project Objective and Relevance

- **Overall Objective:** Develop low cost non-rare earth motor solutions while maintaining high power density, specific power, and efficiency.
  - Develop or use new motor materials.
  - Perform fundamental research to improve motor modeling accuracy.
    - Evaluate impacts of factory stamping upon magnetic/mechanical properties and performance.
    - Develop advanced modeling algorithms.
  - Employ high performance computational tools and resources.
  - Design motors technologies that address DOE EDT 2020 motor targets.

- **FY17 Objectives:**
  - Design, build, and test a PM-free motor that meets DOE targets.
  - Develop/implement high fidelity motor magnetics and loss modeling methods.
  - Implement advanced FEA motor modeling and optimization code on high performance computational cluster and supercomputer.
  - Use micro-magnetics software code to aid with magnetic domain evolution theory, and complement residual stress studies.
  - Formulate fabrication and processing techniques for high efficiency FeSi motor laminations and ultra conductive copper.

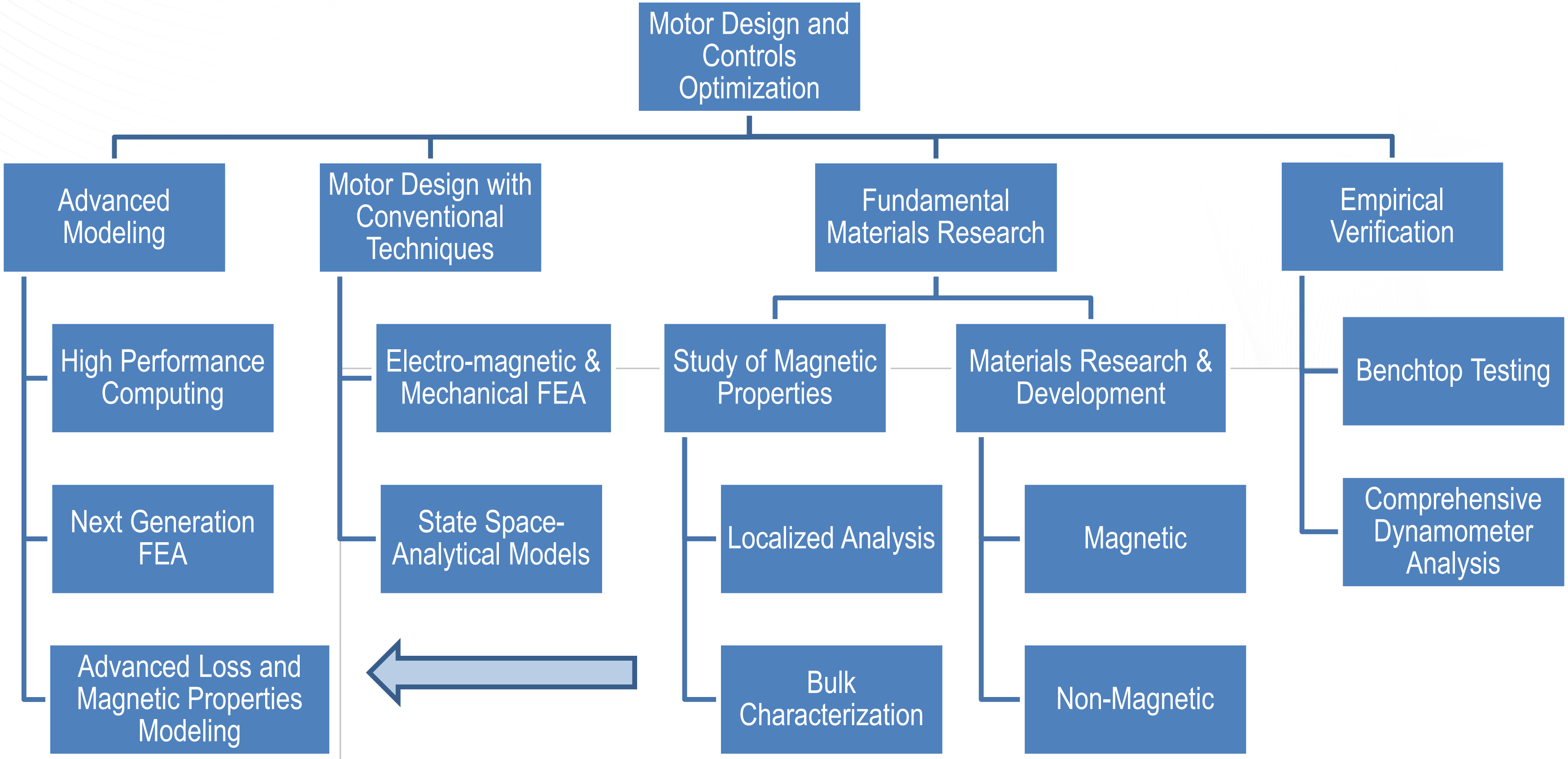
Milestones

Date	Milestones and Go/No-Go Decisions	Status
December 2016	Milestone: Down-select to a subset of motor designs for optimization.	Complete.
March 2017	Milestone: Characterize non-rare earth motor magnet materials.	Complete.
June 2017	Go/No-Go decision: If non-rare earth motor simulations indicate that the design will meet DOE EDT 2020 motor targets, then fabricate proof-of-principle motor prototype.	On track.
September 2017	Milestone: Complete proof-of-principle testing of motor prototype selected in Q3.	On track.

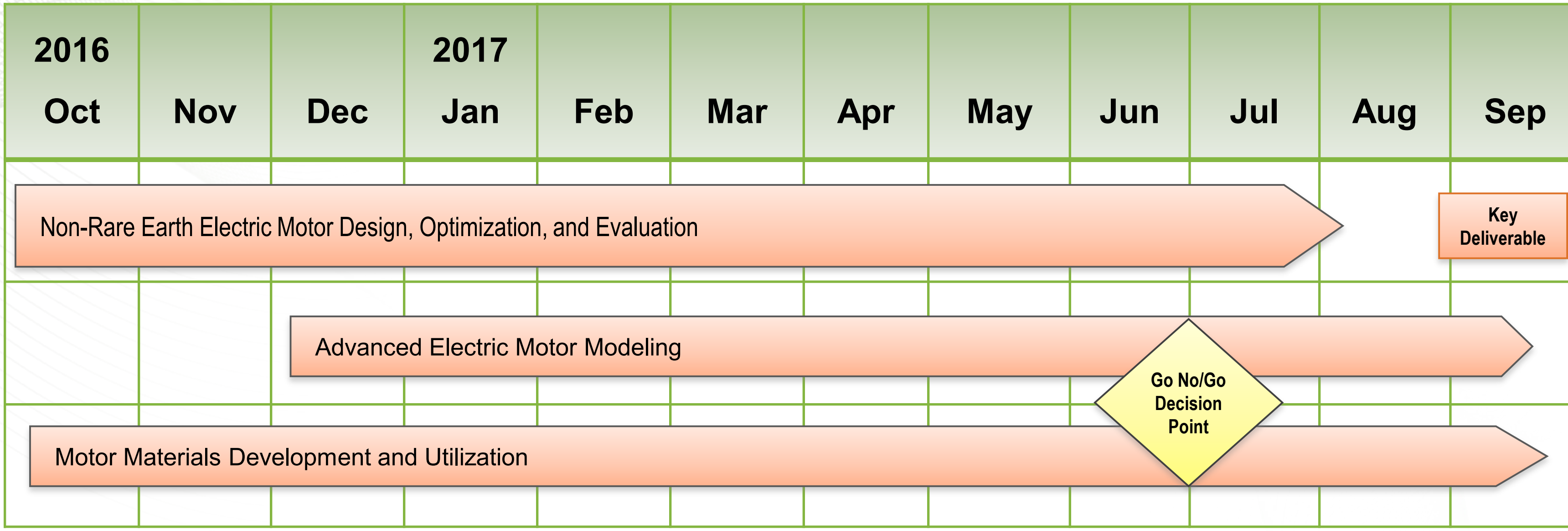
Any proposed future work is subject to change based on funding levels

Approach/Strategy

- Use advanced modeling and simulation techniques to perform design/control optimization of synchronous reluctance motor that does not use rare-earth permanent magnets.
- Develop or use processes/materials that yield high efficiency and increased power density and specific power
- Conduct fundamental research to improve motor modeling accuracy and use new materials



Approach FY17 Timeline



Go No/Go Decision Point: If non-rare earth or reduced rare-earth motor design simulation results indicate that the design will meet DOE EDT 2020 motor targets, then fabricate motor prototype.

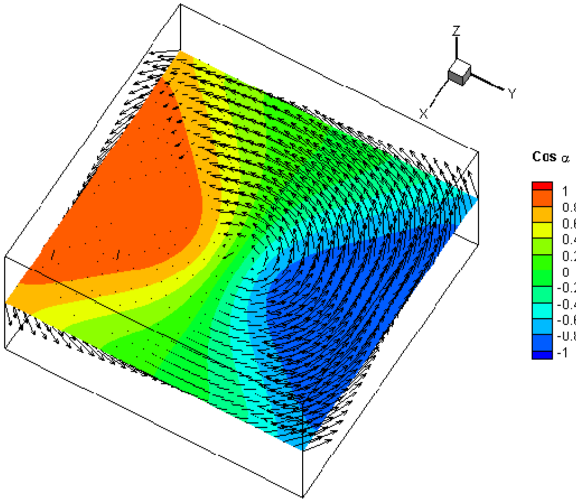
Key Deliverable: Non-rare earth motor prototype.

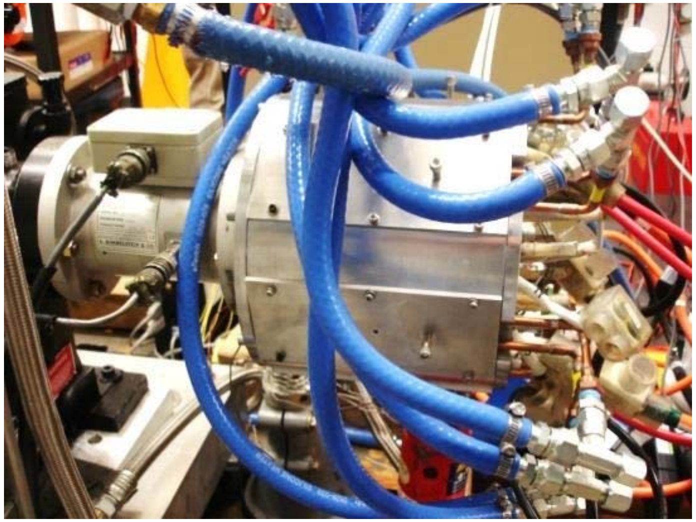
Any proposed future work is subject to change based on funding levels

Technical Accomplishments – Previous Motor Research

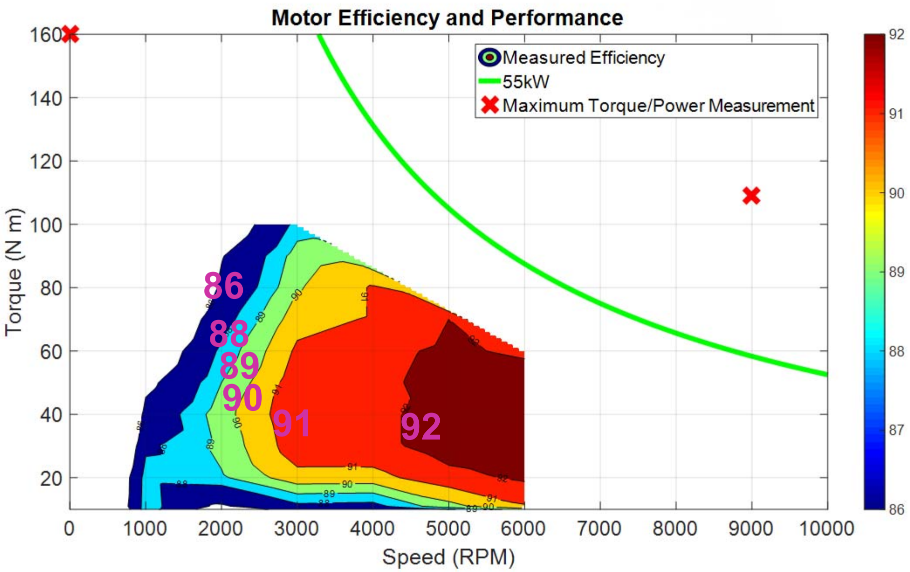
- A new micro-magnetics scaling approach was developed in HPC environment for the transition from a mono-domain to a multi-domain structure
- Initiated development of HPC motor simulation tools with advanced loss analysis
- Designed, built, and evaluated an optimized ferrite permanent magnet motor
  - Achieved 103 kW peak power with low-cost motor that has same volume as 60 kW motor in 2015 Prius
  - Meets DOE 2020 cost and power targets

Magnetic Domain Simulations





ORNL Ferrite Motor Prototype on Dynamometer



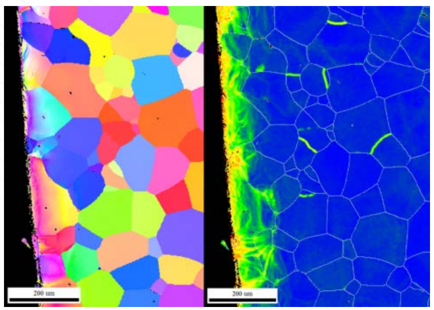
ORNL Ferrite Motor Test Results

FY17 Technical Accomplishments – Advanced Modeling

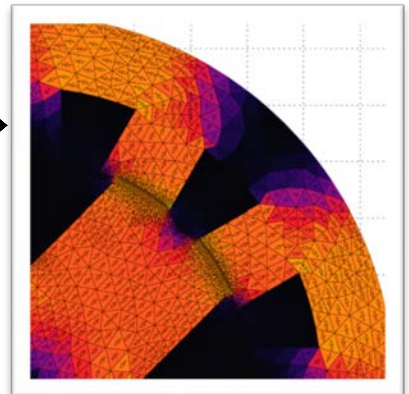
Awarded an allocation of supercomputer 2.25 million core hours
2D FEA code successfully working

Stress Distribution

- Function of cutting/stamping method
- Influenced by mechanical fastening
- Impacted by rotation and other forces

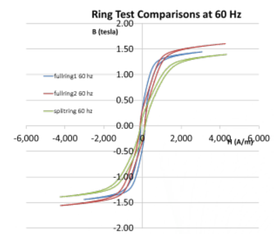


Advanced FEA Modeling Tool

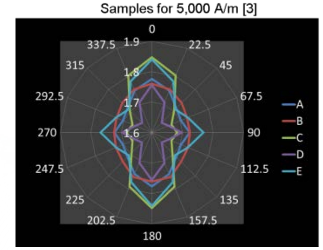


Bulk Characterization

- Traditional Epstein and ring specimen testing at various temperatures
- Custom analysis of rotational losses, anisotropic magnetization/loss, PWM, etc.

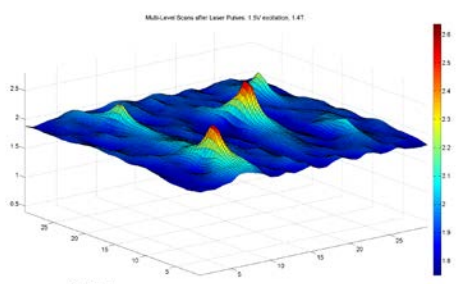


Flux Density (T) in Various 3% Si Steel Samples for 5,000 A/m [3]



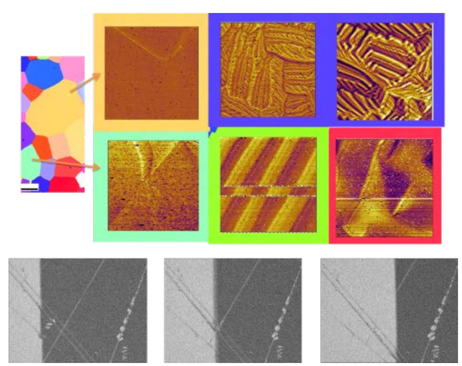
Localized Magnetic Properties

- Function of stress distribution
- Magnetization and loss characteristics are not homogeneous



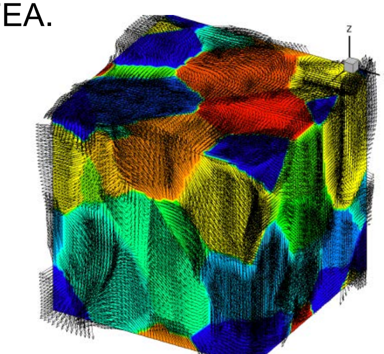
Empirical Magnetic Domain Analysis

- Traditional Epstein and ring specimen testing
- Impacts of stress, pinning, etc. upon domain wall movement, and ultimately magnetization/loss properties.



Theoretical Magnetic Domain Analysis

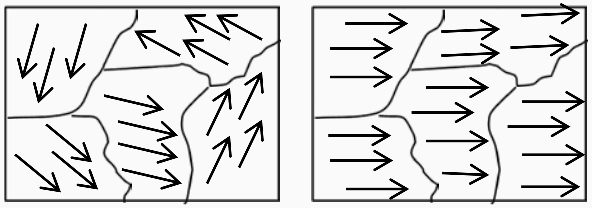
- Fundamental theory to confirm and supplement empirical findings.
- Indirect link to FEA - too computationally intensive for direct use in FEA.



FY17 Technical Accomplishments – Magnetic Domains

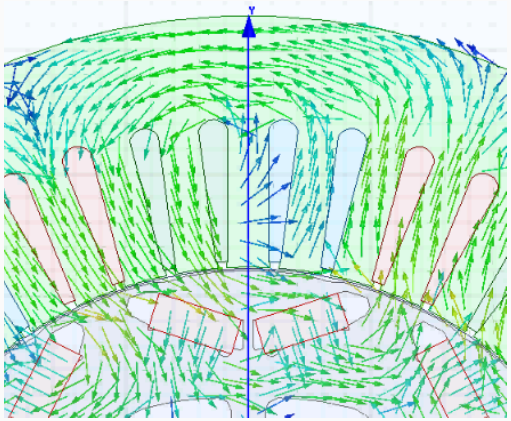
Advanced Modeling of FeSi Magnetic Properties

- Micromagnetics code/simulation space has been expanded to a larger scale to include multiple domains using unique scaling techniques and high performance computing.
- Complements experimental domain wall observation.
- Includes consideration of various interaction energies at the atomic scale, externally applied fields and elastic strains.



FeSi Without Applied Field

FeSi With Applied Field

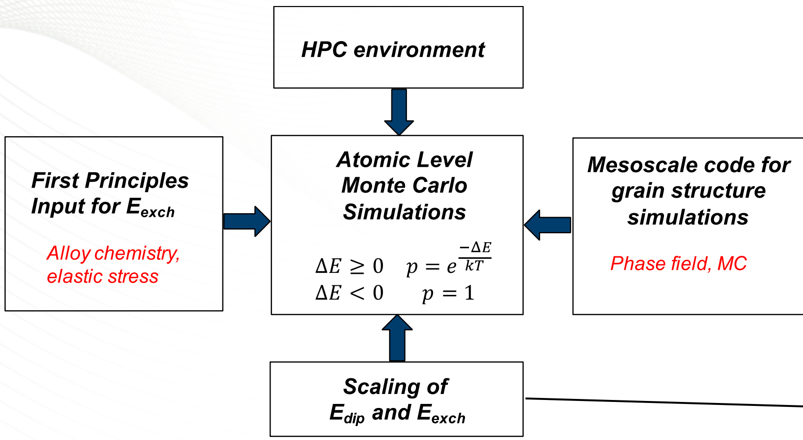


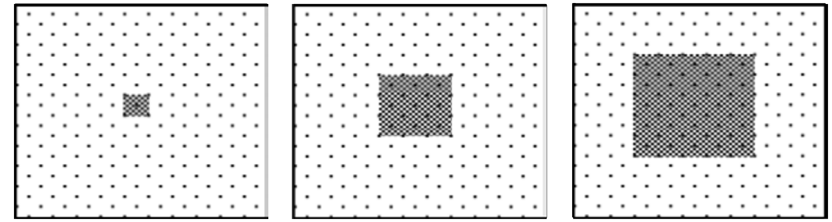
Example with varying magnetization vectors in an electric motor

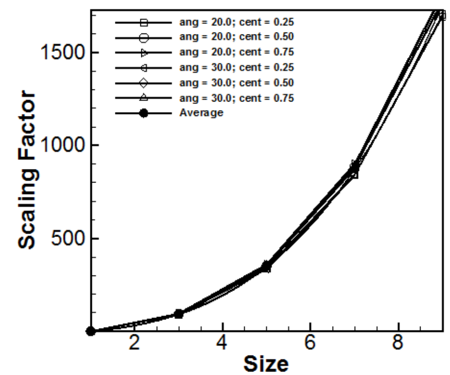
Magnetic domain research provides deeper insight into factors that impact magnetization and loss properties, thereby facilitating improved modeling accuracy and material development efforts.

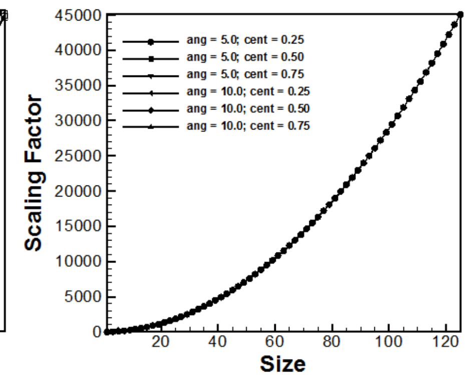
FY17 Technical Accomplishments – Magnetic Domains

Micromagnetics Simulation and Scaling

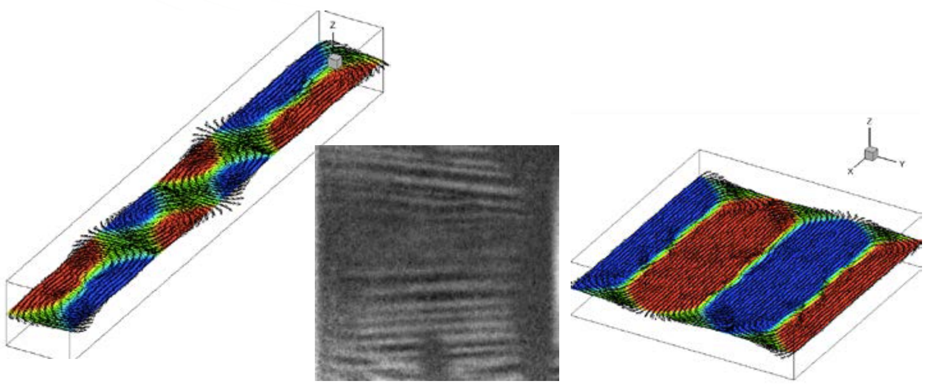








- Developed a new approach to scale E_{dip} and E_{exch} energies a function of the simulation volume
- Scaling allows performing simulations at the atomic scale while expressing the energies at each atomic site at an “effective” length scale of many atoms



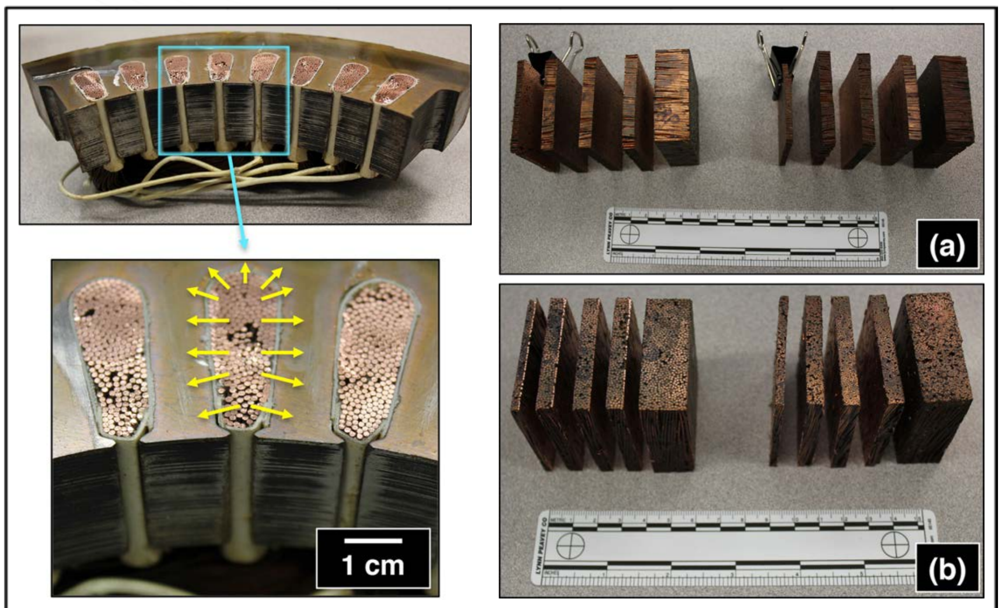
In the presence of elastic strain, island domains (left) disappear and striped domains (right) appear. Simulation results in agreement with bulk domains in Fe-3%Si grain oriented steel measured using neutron diffraction (middle)

B. Radhakrishnan, M. Eisenbach and T.A. Burress, “A New Scaling Approach for the Mesoscale Simulation of Magnetic Domain Structures using Monte Carlo Simulations, J. Magnetic Materials, 2017

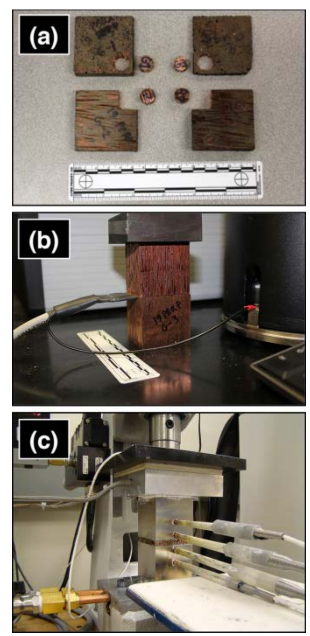
FY17 Technical Accomplishments – Winding Analysis

- Specimens fabricated for thermal measurements (in collaboration with NREL – Bennion and Cousineau)
- Thermal transfer in windings is transversely isotropic
- Thermal conductivity perpendicular to wires about 100x slower than parallel to wires (~ 200 W/mK for latter)

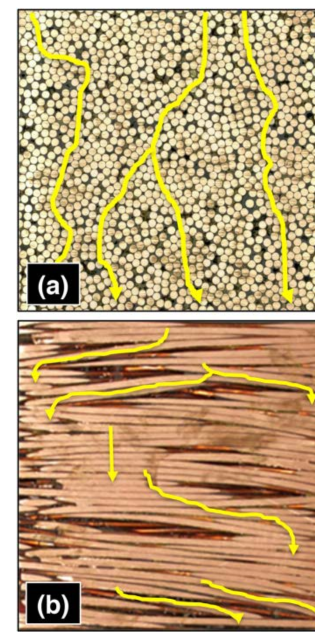
Heat transfers perpendicular to copper windings into stator laminates if no end-turn cooling is implemented.



Flash diffusivity, transient plane, and thermal transmittance methods used for thermal measurements



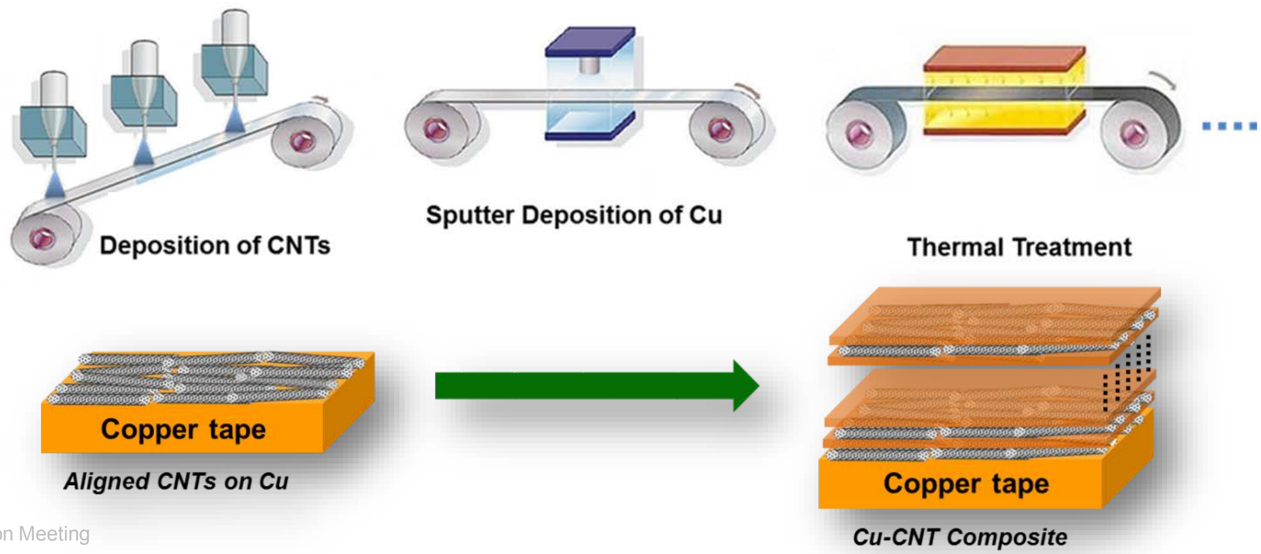
Percolation pathways affected thermal transfer



FY17 Technical Accomplishments - Ultra Conductive Copper

- Initiated implementation of process for a composite material consisting of carbon nanotubes (CNT) embedded in Cu matrix – Ultra Conductive Copper (UCC)
- CNTs have extraordinary electrical, thermal properties compared to Cu:
  - 100x higher current density, 10x higher thermal conductivity, 4.5-6x lighter weight, 300x higher tensile strength
  - Change in ρ is not sensitive to temperature
- Issues associated with mass production and incorporation into electric motors is being addressed.

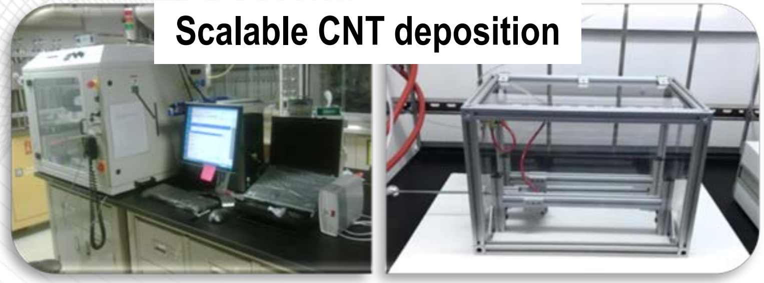
Our approach is suitable for in-line roll-to-roll UCC commercial manufacturing process



FY17 Technical Accomplishments - Ultra Conductive Copper

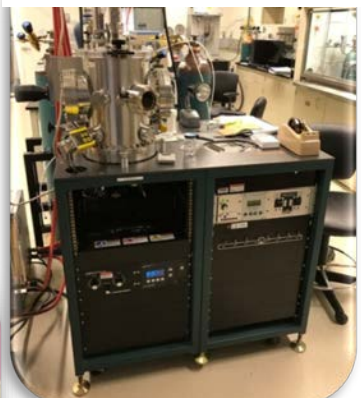
Lab Setup for Processing

Scalable CNT deposition

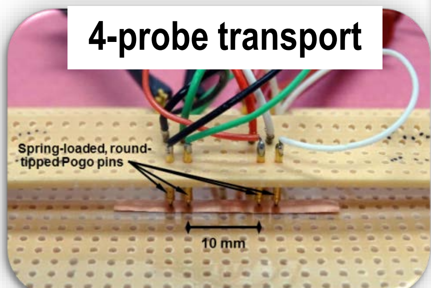


Vacuum annealing

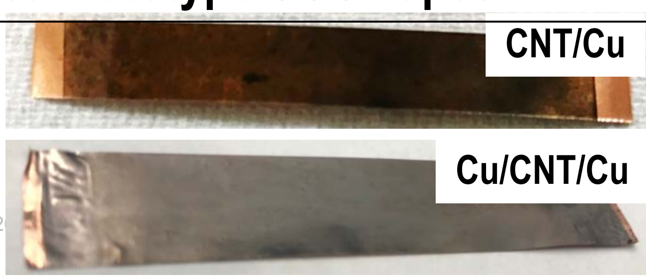
Metal film deposition



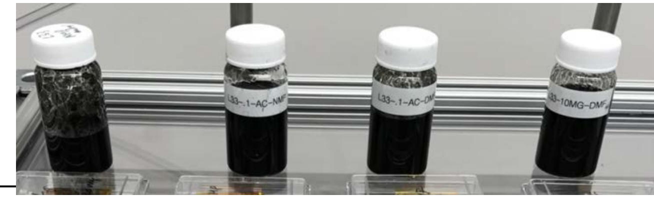
4-probe transport



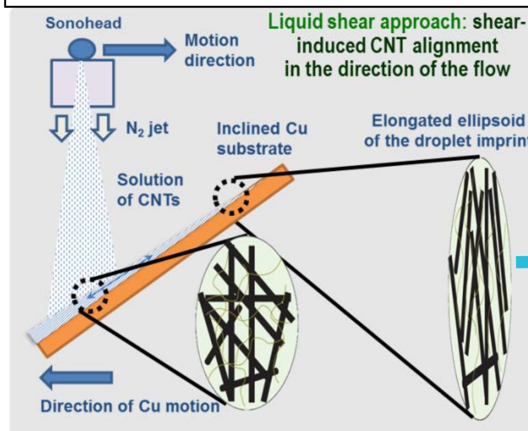
First Prototype UCC Tapes Produced



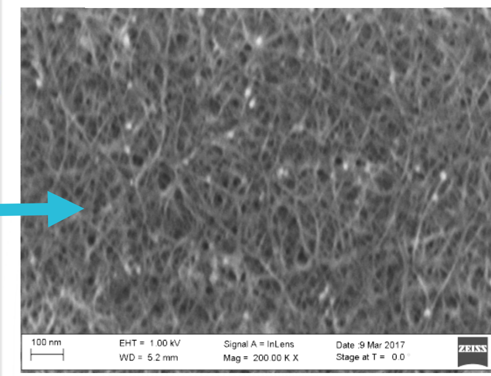
Created Stable CNT Dispersion Formulations



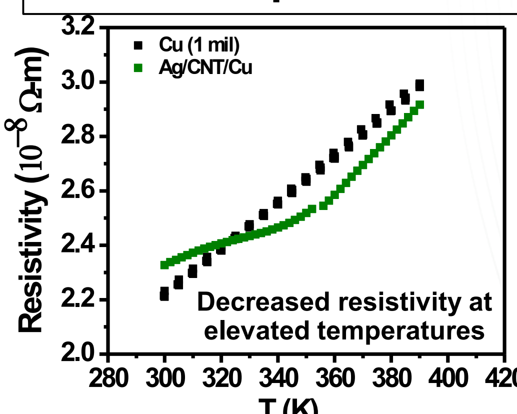
Demonstrated that alignment of CNTs on Cu is possible using our fabrication approaches

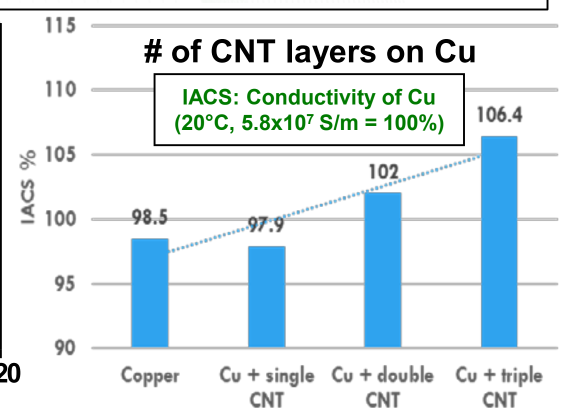


Aligned CNTs on Cu



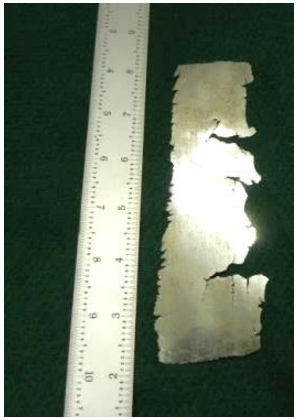
Verified Improvement in Electrical Conductivity



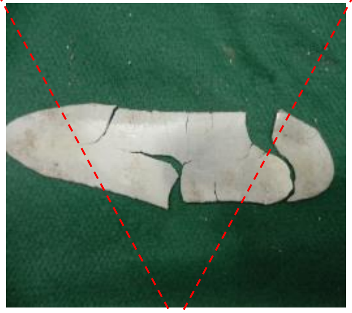


FY17 Technical Accomplishments – High Efficiency FeSi

- A new processing sequence was developed to successfully roll Fe-6%Si-X alloy
- Using the new thermomechanical processing (TMP) approach, a 75% reduction in thickness by room temperature rolling
- Further optimization of processing parameters and steel chemistry to improve consistent rolling performance is under way
  - Modeling and simulation is being used to understand the fundamentals of atomic ordering and embrittlement to design modified Fe-6%Si-X alloys with increased RT ductility



Successful rolling of Fe-6Si-X at room temperature to roughly 75% reduction in thickness to a final thickness of ~0.4 mm



Unsuccessful rolling of Fe-6Si-200ppm B alloy hot rolled to 0.25” in the 1100°C-900°C range, rapidly cooled and immediately cold rolled at room temperature

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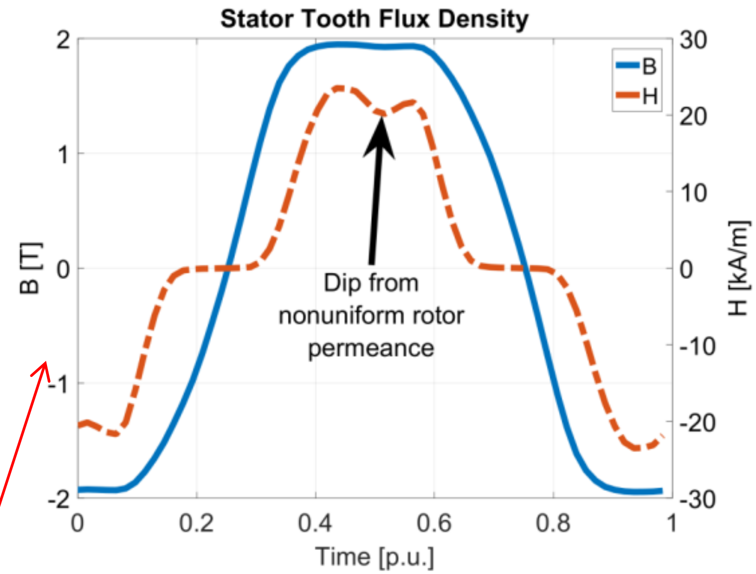
FY17 Technical Accomplishments – Loss Modeling

- Developed accurate core losses and magnetic hysteresis prediction models over a wide range of excitation amplitudes and frequencies. This approach
  - Couples low-frequency Preisach hysteresis model with dynamic finite-element model
  - Allows modeling of hysteresis with knowledge only of low-frequency hysteresis behavior and core geometry
  - Will be utilized in a motor design simulation tool with hysteretic material properties
- Most loss post processing methods rely on the assumption of sinusoidal flux density, but this approach accounts for non-sinusoidal behavior
- When operated near saturation, electric machines exhibit less ideal behavior
  - Yields trapezoidal flux waveform
  - H-field harmonics due to stator/rotor slotting interactions



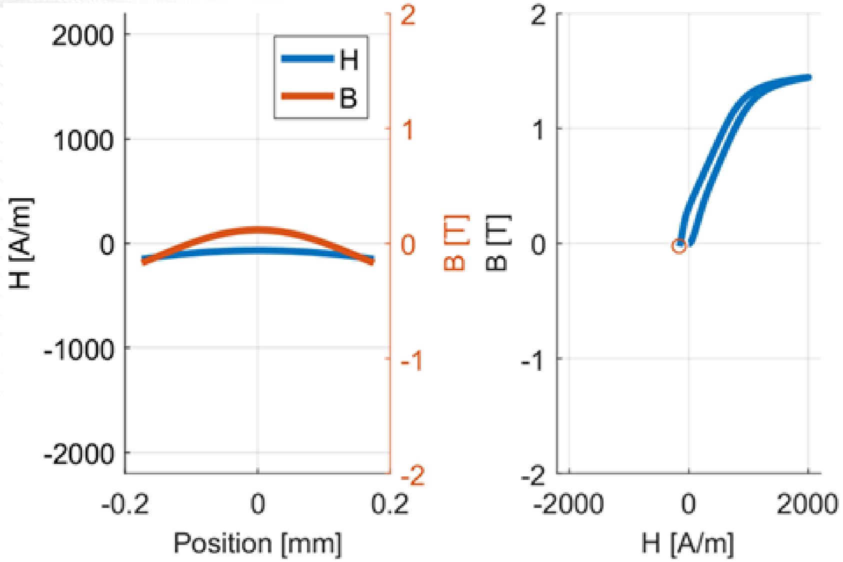
Measured Epstein Frame Loss Density B = 1.925T, f = 120Hz	
Ideal Sinusoid	9.38 W/kg
Real Waveform	14.65 W/kg

Losses increase by 56% compared to the non-ideal case due to much higher $\frac{\partial B}{\partial t}$ values in the transition region.

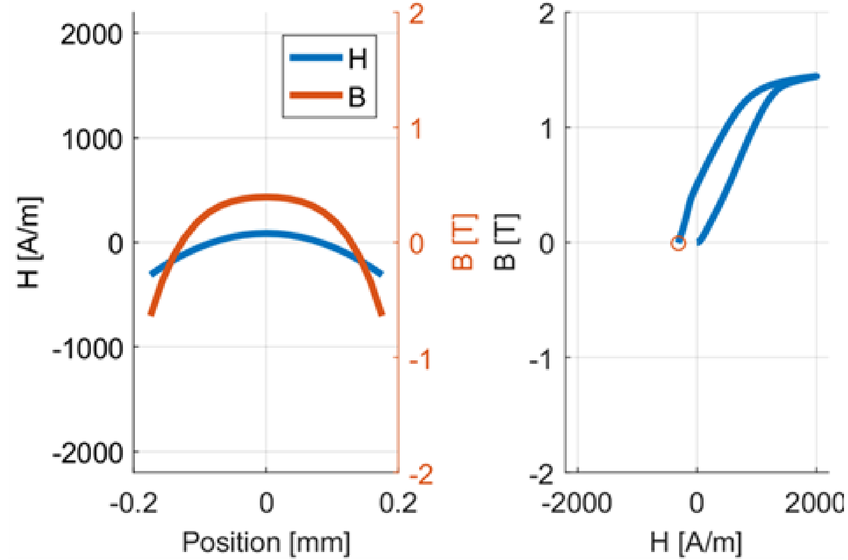
FY17 Technical Accomplishments – Loss Modeling

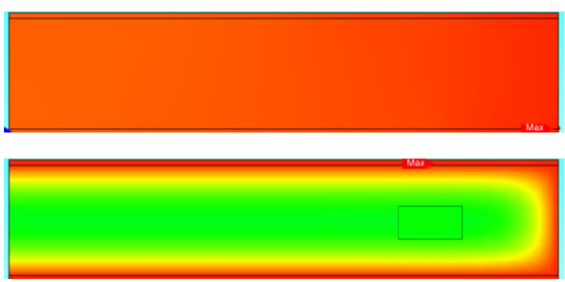
Distribution of B and H fields throughout thickness of lamination at high frequencies shows significant variation

100Hz

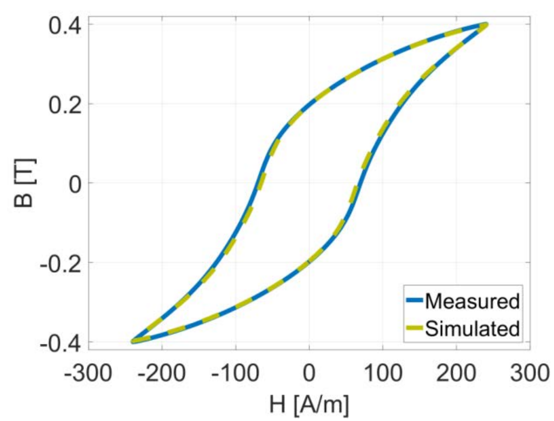


1000 Hz

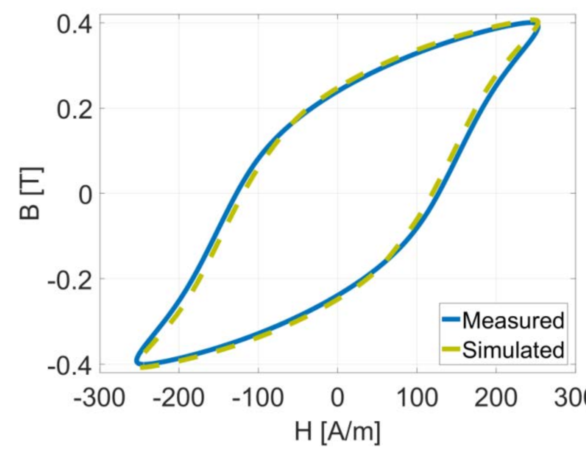




Lamination eddy current density at 10Hz (top) and 1kHz (bottom)



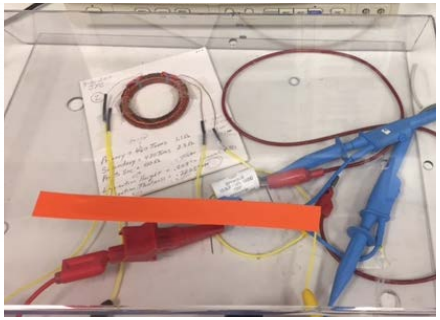
Dynamic B-H loop at 50Hz

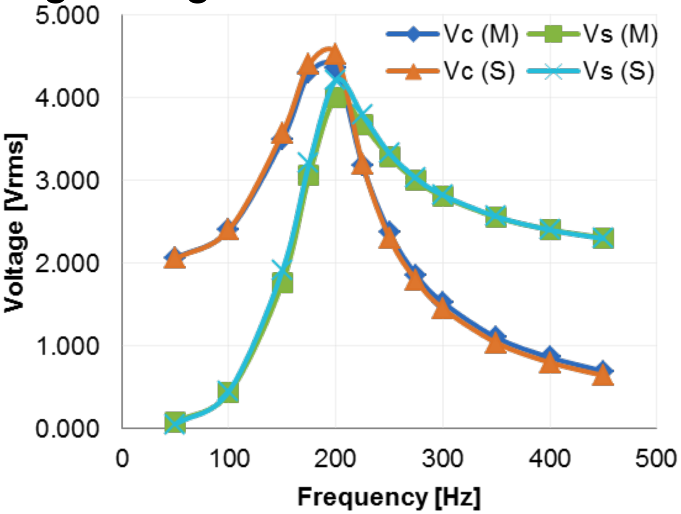


Dynamic B-H loop at 500Hz

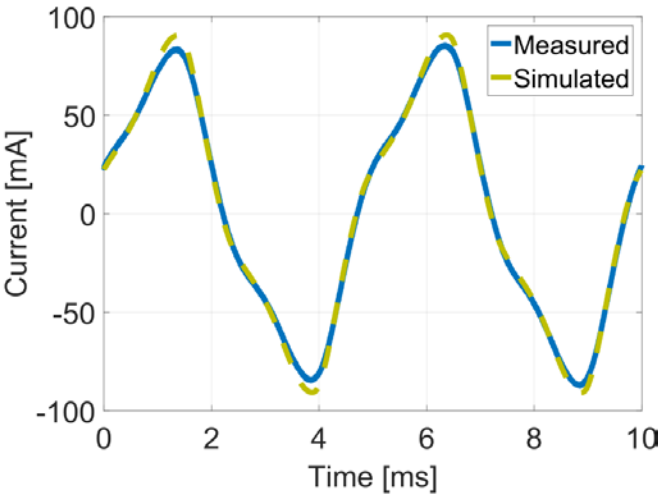
FY17 Technical Accomplishments – Loss Modeling

Empirically verified newly developed hysteresis model by simulating/measuring inductor magnetics in FEA and corresponding voltage in resonant LC circuit

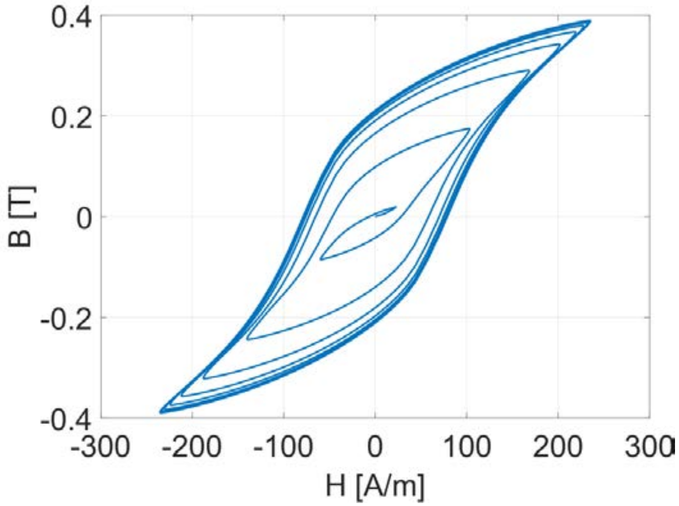




Resonant circuit response for 2Vrms input



Resonant circuit current waveform at 200Hz

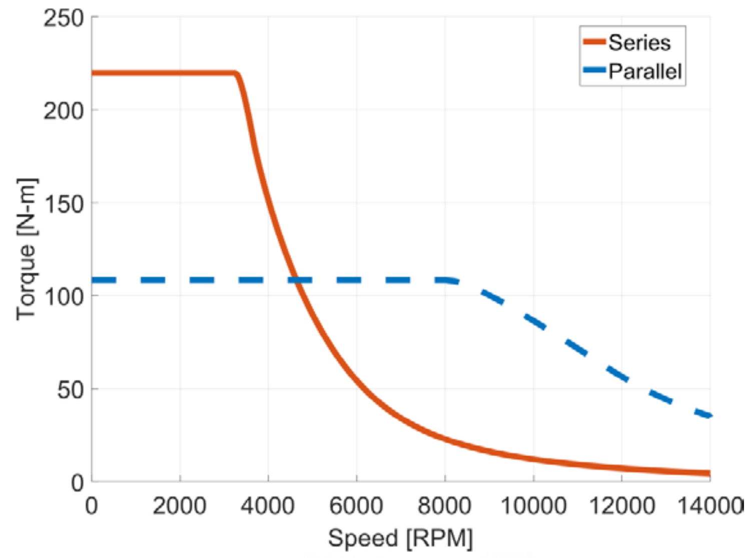


Simulated transient hysteresis behavior with increasing frequency

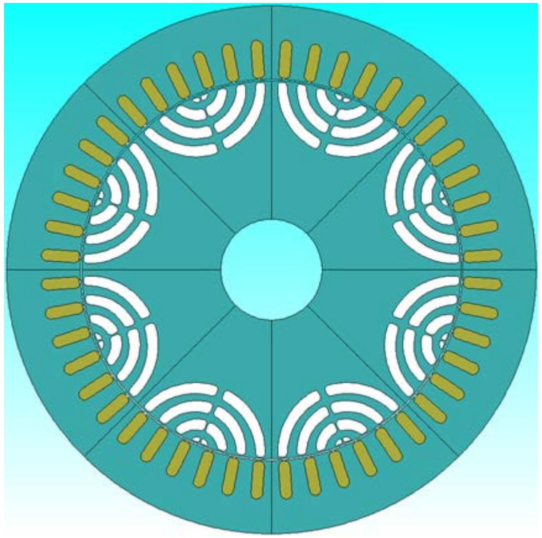
FY17 Technical Accomplishments – Motor Design

- Completed design and optimization of reconfigurable-winding synchronous reluctance (SynchRel) machine
- Occupies same volume as 60 kW 2015 Prius, while simulations show over 90kW is possible in parallel mode.

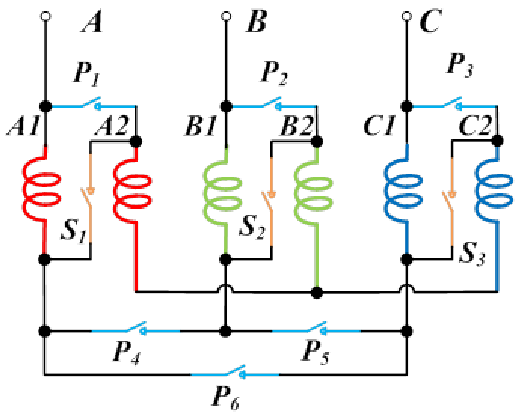
Simulated Torque-Speed Curve



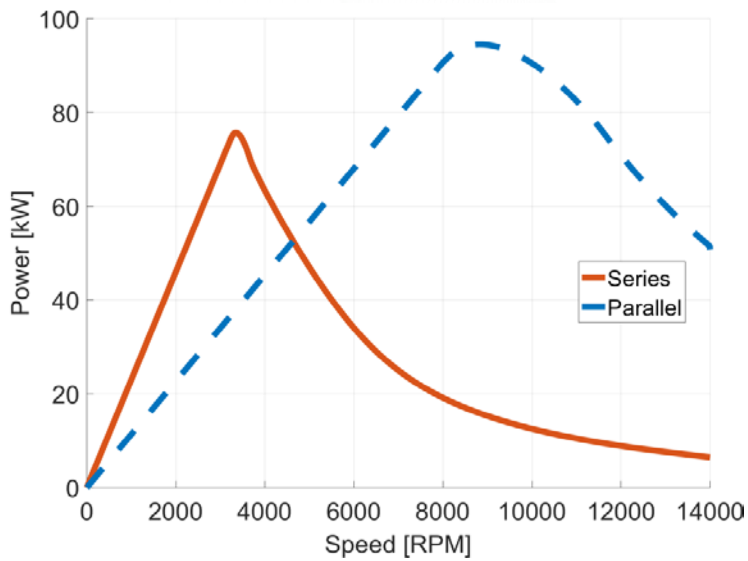
Nominal Synchronous Reluctance Machine Design



Stator winding/switch configuration



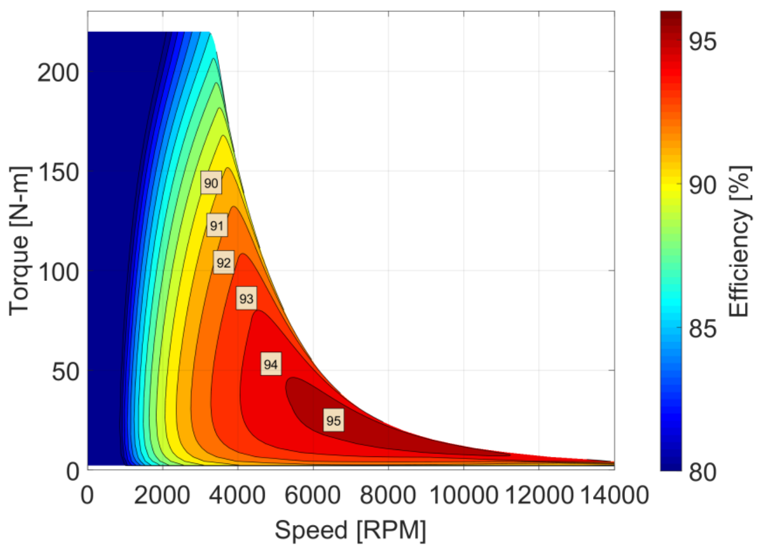
Simulated Power-Speed Curve



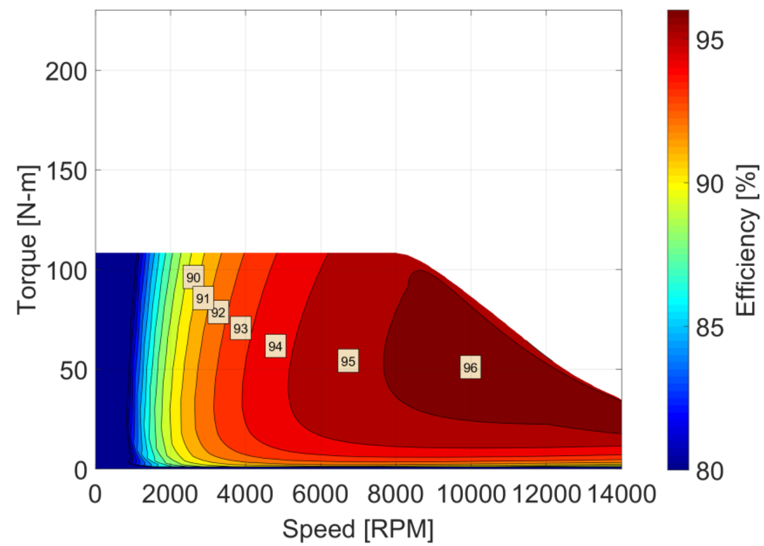
FY17 Technical Accomplishments – Motor Efficiency

- Efficiency maps 150C winding temperature including thyristor losses
- Note the large high efficiency region in parallel mode for low torque/high speed

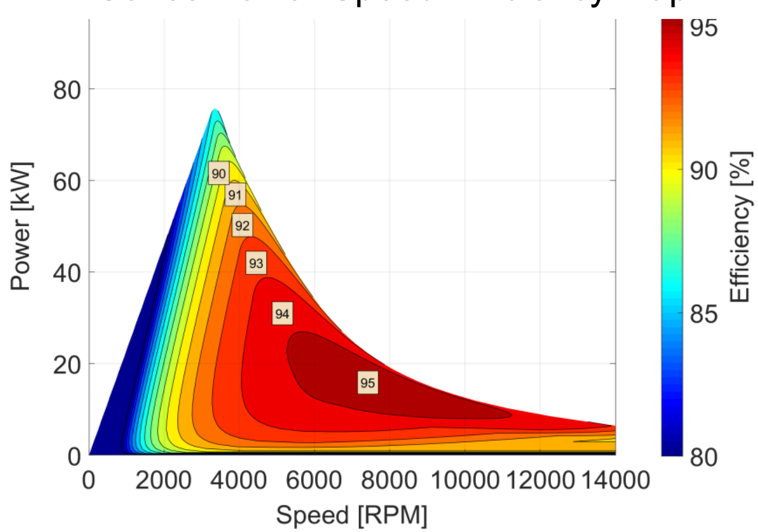
Series Torque-Speed Efficiency Map



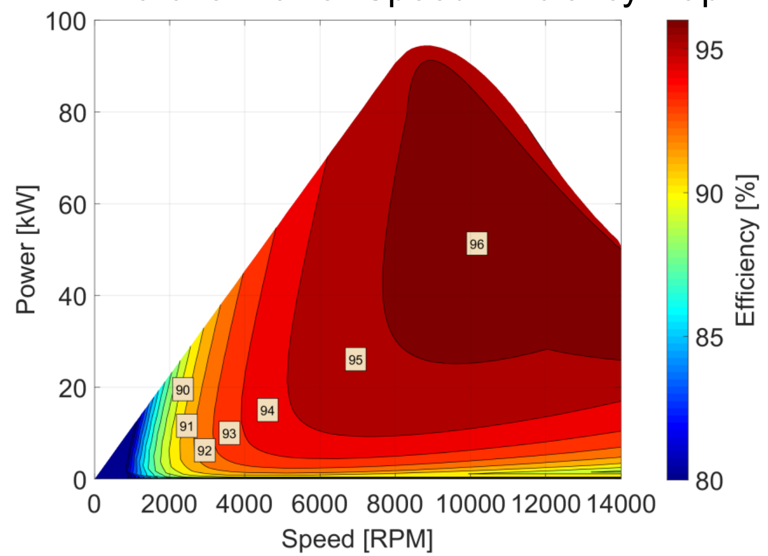
Parallel Torque-Speed Efficiency Map



Series Power-Speed Efficiency Map



Parallel Power-Speed Efficiency Map



Partners/Collaborators

Logo	Organization	Role
	University of Wisconsin - Madison	Collaborating on motor design and FEA studies.
	NREL	ORNL will provide heat generation map throughout motor for NREL to develop and provide feedback on integrated cooling techniques.
	AMES	ORNL will test magnet samples produced by AMES and is attending DREAM project review meetings, workshops, and WebEx updates to keep up to date on non-RE PM alternative development, and keeping design options available for use of new PM developments from AMES.

Remaining Challenges and Barriers for FY17

- Maintaining consistency of mechanical and magnetic properties for small prototype batches of high efficiency steel desirably to be used in prototype motor.
- Implementation of material processing developments on a massive scale.

Any proposed future work is subject to change based on funding levels

Proposed Future Work

- **Remainder of FY17**
  - Use results from evaluation and materials research to design, build, and test full scale prototype.
  - Scale FEA to large HPC system

- **FY18**
  - Continue incorporating detailed theoretical and experimental findings using advanced FEA modeling method.
  - Perform final design optimization and build/evaluate final prototype.

Any proposed future work is subject to change based on funding levels

Summary

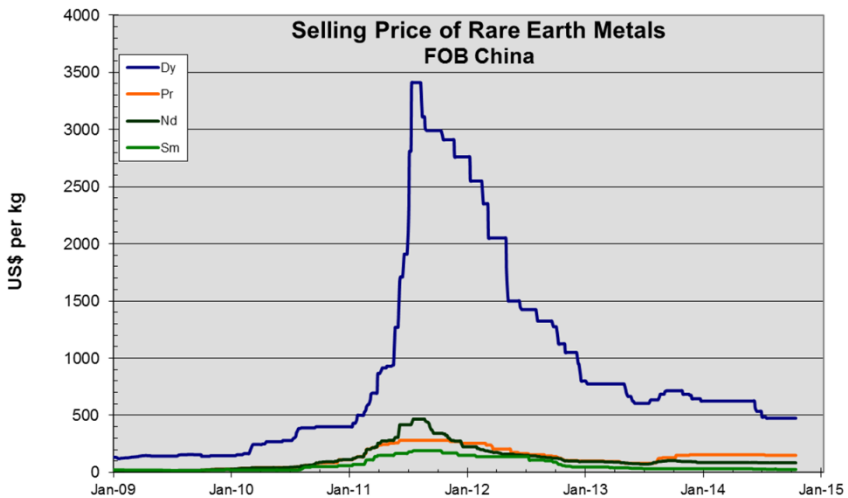
- **Relevance:** The objective is to develop low cost non-rare earth motor solutions while maintaining high power density, specific power, and efficiency to meet DOE targets.
- **Approach:** Use advanced modeling and simulation techniques and develop/research materials to help optimize performance of various electric motor types.
- **Collaborations:** Interactions are ongoing with other national laboratories, industry, and other government agencies.
- **Technical Accomplishments:** Design and modeling efforts have produced several promising motor technologies, custom characterization tools have been developed to conduct magnetic materials research, and advanced model developments are underway.
- **Future work:**
  - FY18: Use results from evaluation and materials research to design, build, and test prototype.
  - Continue incorporating detailed theoretical and experimental findings using advanced FEA modeling method.
  - Perform final design optimization and build/test final prototype

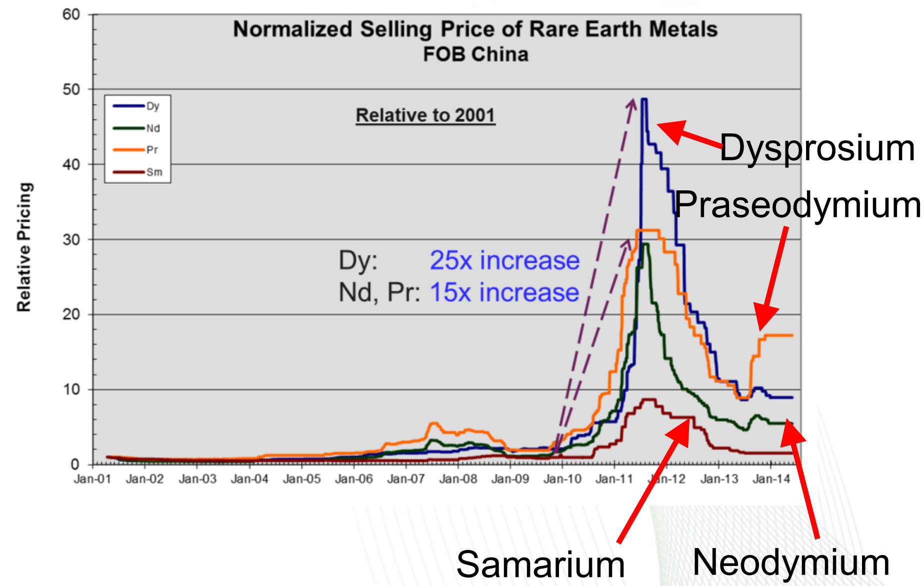
Any proposed future work is subject to change based on funding levels

Technical Backup Slides

Technical Backup

- Rare earth (RE) permanent magnet (PM) motors that dominate the EV/HEV motor market are not cost effective.
  - RE elements in PMs contribute up to 78% of the total DOE EDT 2020 electric motor cost target
    - Currently 30-50% of actual cost
  - Uncertainty in RE material availability and the likelihood that metallurgical separation processes for heavy RE mean that pricing will remain high over the near term and longer

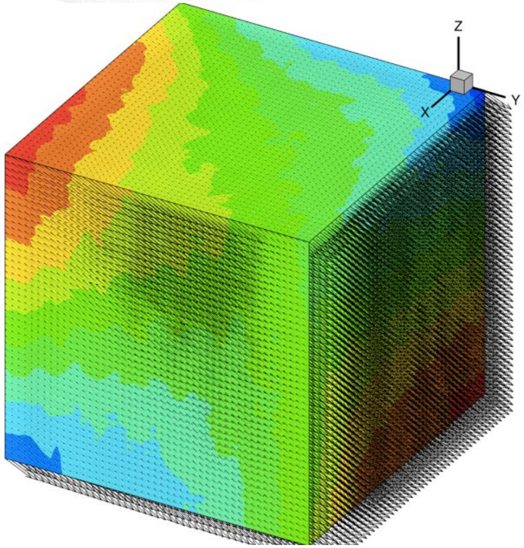




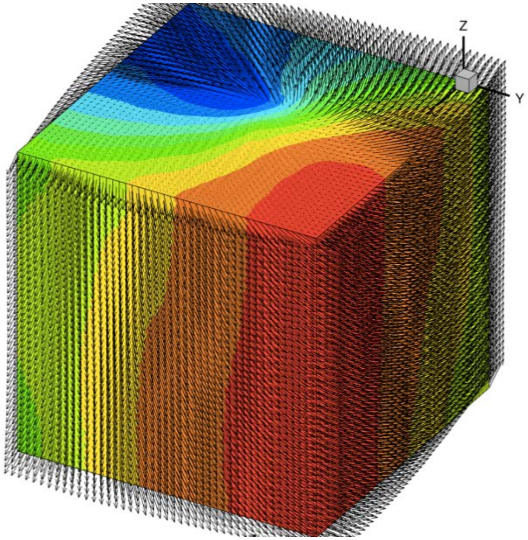
Source: Steve Constantinides, Arnold Magnetics

Technical Backup

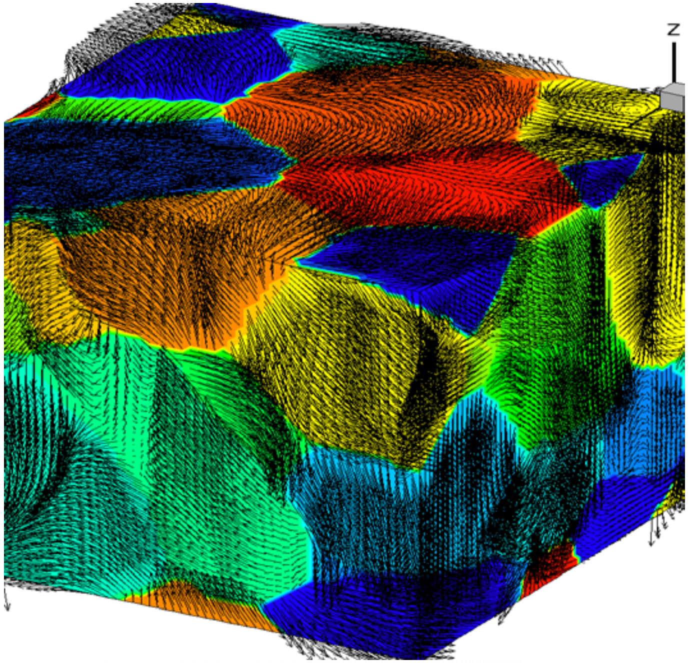
Advanced Modeling of FeSi Magnetic Properties



Simulations with 190 million atoms do not show the formation of domains.



Domains appear when simulation size reaches 2.2 billion atoms. This is accomplished by using unique scaling techniques and HPC.

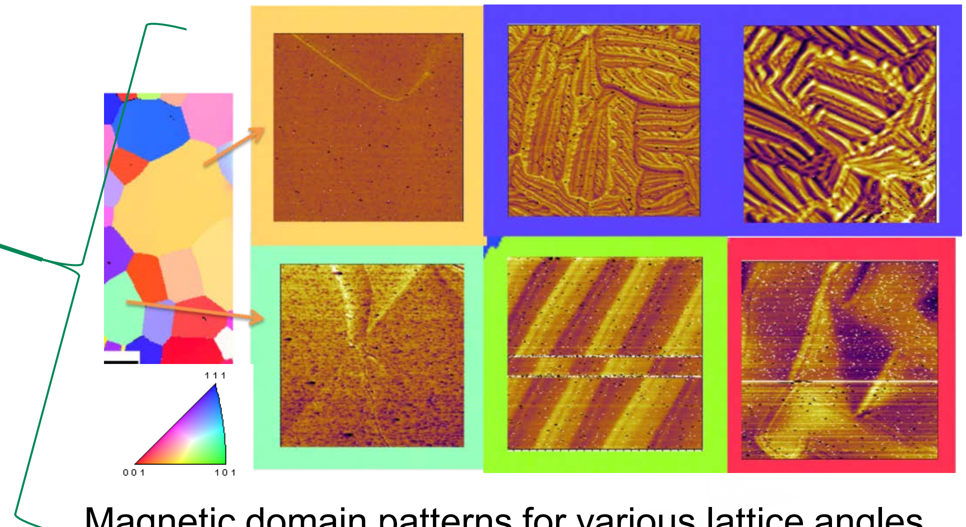


Simulation with grain structure and about 700 billion atoms

- Formation of domains inside individual grains clearly seen
- Tendency to form domains increases with scaling

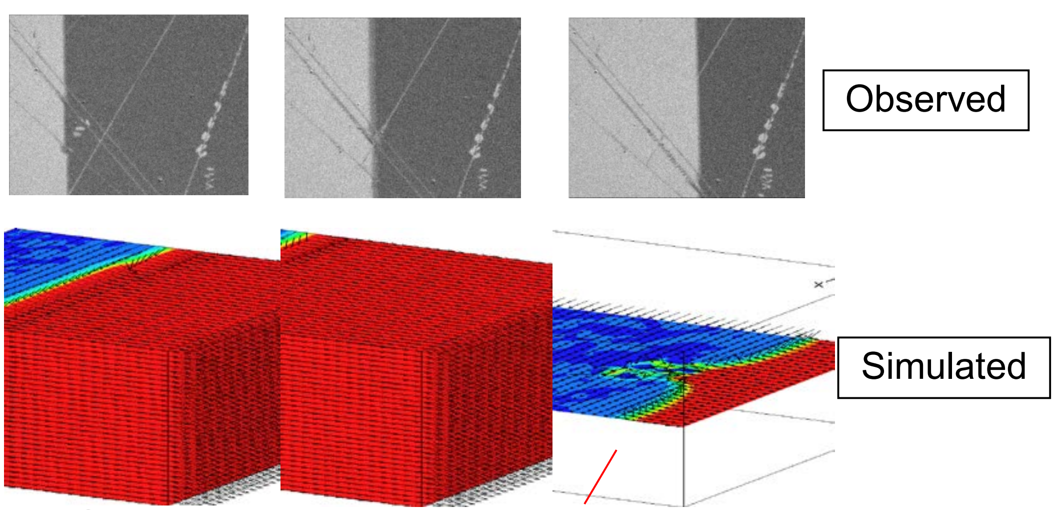
Technical Backup – Magnetic Domain Background

- Atomic force microscopy (AFM) analysis of magnetic domains near deformation zone.
- Impacts of pinning, residual stress, etc. upon domain wall movement are being characterized.
- Provides experimental input for validation of detailed domain simulations and their evolution during magnetization (B-H curve).
- Scanning on the order of 200µm x 200µm per day.

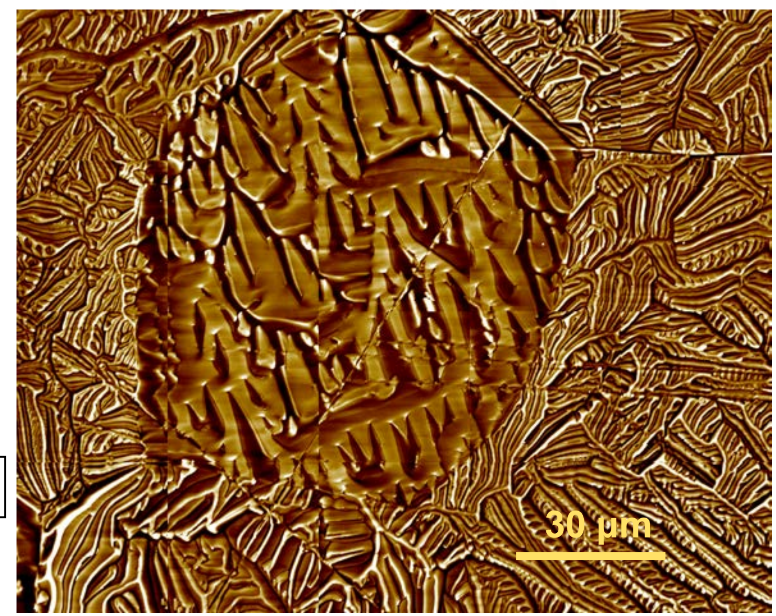


Magnetic domain patterns for various lattice angles

Domain wall movement with applied AC field



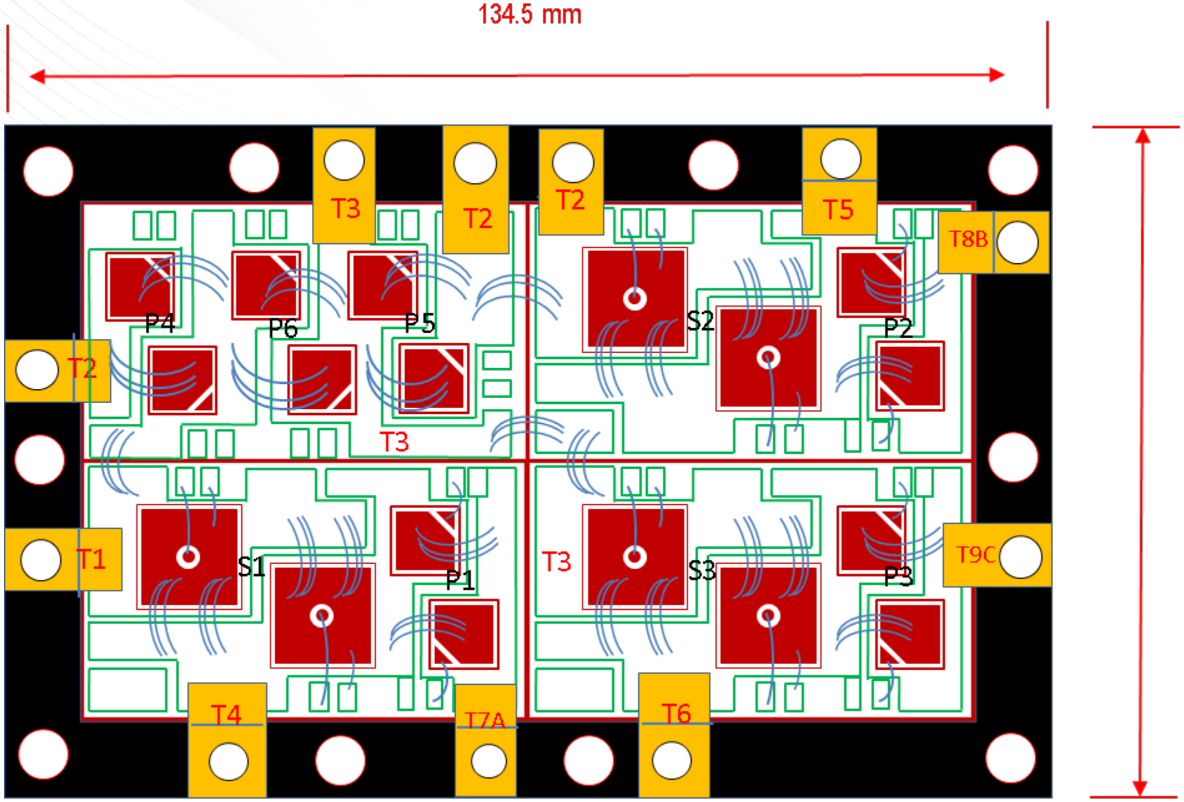
Domain wall pinning by non-magnetic obstacle



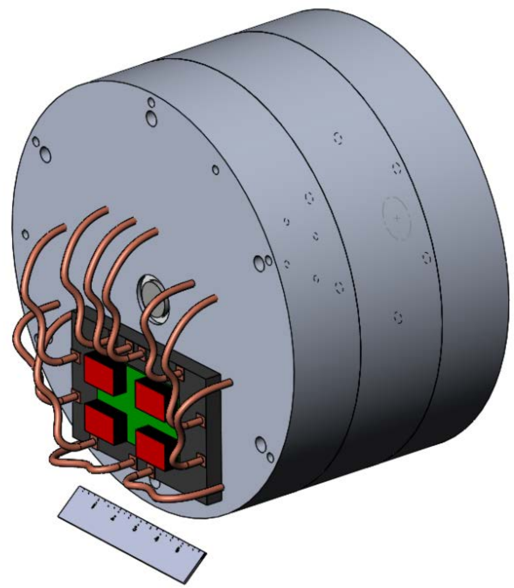
Misoriented magnetic domains – Large Scan Area

Technical Backup – Switchbox

Thyristor switchbox design completed
134.5 x 86.4 mm = 5.3” x 3.4”



Example of installation



Technical Backup

ORNL prototype specifications

	Series	Parallel
Peak Torque	219N-m	108N-m
Peak Power	75kW	94kW
Corner Speed	3200RPM	8000RPM
Diameter: •Stator •+ Housing	 •9.75” •12.0”	
Length: •Stack •+ End Turns •+ Housing	 •2.75” •5.75” •7.00”	
Volume: •Active •+ End Turns •+ Housing •+ Switch Box[1]	 •3.37L •7.05L •13.0L •13.4L	
Operating Voltage	$600V_{dc}$	
Phase Current	$220A_{rms}$	

	Series	Parallel
Torque Density: •Active •+ End Turns •+ Housing •+ Switch Box	 •65.0N-m/L •31.0N-m/L •16.8N-m/L •16.3N-m/L	 •32.0N-m/L •15.3N-m/L •8.30N-m/L •8.06N-m/L
Power Density: •Active •+ End Turns •+ Housing •+ Switch Box	 •22.2kW/L •10.6kW/L •5.77kW/L •5.60kW/L	 •27.8kW/L •13.3kW/L •7.23kW/L •7.01kW/L